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INFLUENCE OF CRYSTAL ORIENTATION ON FRICTION CHARACTERISTICS OF TITANIUM SINGLE CRYSTALS IN VACUUM

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Lewis Research Center

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SUMMARY

Friction experiments were conducted in vacuum (10^{-9} mm Hg) with oriented single-crystal titanium rider specimens sliding on polycrystalline titanium disk specimens. Experiments were conducted at a surface speed of 2.28 centimeters per second and loads from 250 to 1000 grams. Two principal single-crystal orientations were examined, one with the primary prismatic slip plane $\left((10\bar{1}0)\right)$ oriented parallel to the sliding interface and the other with the basal plane $\left((0001)\right)$ oriented in this same direction.

The friction coefficient for titanium single crystals was less with the prismatic slip plane (primary slip plane for titanium) oriented parallel to the direction of sliding than with the basal slip plane oriented in this direction. These results correlate with the shear stress data for the respective orientations. Recrystallization and texturing occurred at high loads on the single-crystal surface, and friction values were the same as for polycrystalline titanium.

INTRODUCTION

The crystal structure of metals has been shown to influence their friction properties markedly (refs. 1 to 4). Metals possessing hexagonal crystal structures exhibit lower friction coefficients and lower wear rates than do most face-centered or body-centered cubic metals. For a number of metals which undergo crystal transformations from the hexagonal crystal form to either body- or face-centered cubic, a marked increase in friction, wear, and welding tendencies occurs with transformation to the cubic form. The slip mechanisms in the hexagonal metals have been shown to have a definite influence on friction. Those metals possessing basal slip exhibit lower friction coefficients than metals, like titanium, where prismatic slip (multiple slip planes) occurs. In reference 5, with single crystals of cobalt oriented to have various planes parallel to the direction of sliding, the lowest friction was obtained when the basal plane was parallel to the direction of sliding.

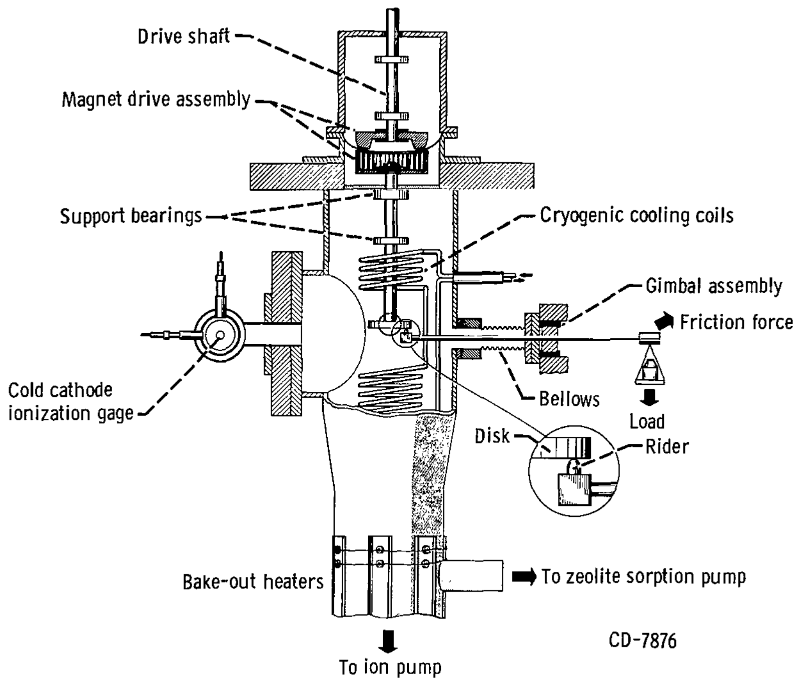


Figure 1. - High-vacuum friction and wear apparatus.

With titanium metal, unlike many other hexagonal metals, the primary slip planes are the prismatic planes $\left((10\bar{1}0)\right)$ rather than the basal planes $\left((0001)\right)$ (refs. 6 and 7). The reason is that titanium deviates considerably from the ideal stacking for closely packed structures. Titanium should, therefore, exhibit lower coefficients of friction with the $(10\bar{1}0)$ planes parallel to the sliding interface than with the (0001) plane parallel to the sliding interface.

The objectives of this investigation were to determine for titanium single crystals (1) the influence of crystallographic orientation on the friction of titanium, (2) the possibility of interfacial recrystallization, and (3) the relation of single-crystal friction data to those for polycrystalline titanium.

APPARATUS AND PROCEDURE

The apparatus used in this investigation is shown in figure 1. The basic elements of the apparatus were the specimens (a $2\frac{1}{2}$-in.-diam. flat disk and a 3/16-in.-rad. rider) mounted in a vacuum chamber. The disk specimen was driven through a magnetic drive coupling. The coupling had two 20-pole magnets 0.150 inch apart with a 0.030-inch diaphragm between magnet faces. The driver magnet that was outside the vacuum system was coupled to a hydraulic motor. The second magnet was completely covered with a nickel-alloy housing and was mounted on one end of the shaft within the chamber. The end of the shaft that was opposite the magnet contained the disk specimen.

The rider specimen was supported in the specimen chamber by an arm that was mounted on gimbal bearings and bellows sealed to the chamber. A strain-gage linkage at the end of the retaining arm, external to the vacuum system, was used to measure frictional force. Load was applied through a dead-weight loading system.

Attached to the lower end of the specimen chamber were a 400-liter-per-second ionization pump and a zeolite sorption force pump. The pressure in the chamber was measured adjacent to the specimen with a cold-cathode ionization gage. In the same plane as the specimens and ionization gage was a diatron-type mass spectrometer (not shown in fig. 1) for determination of gases present in the vacuum system. A 20-foot-long stainless-steel coil of 5/16-inch diameter was used for liquid-nitrogen and liquid-helium cryopumping of the vacuum system.

Specimen Finishing and Cleaning Procedure

The disk specimens used in the friction experiments were finished to a roughness of 4 to 8 microinches. Before each experiment, the polycrystalline disks and the riders were given the same preparatory treatment: (1) thorough rinsing with acetone to remove oil and grease, (2) polishing with moist levigated alumina on a soft polishing cloth, and (3) thorough rinsing with tap water followed by distilled water. For each experiment, a new set of specimens was used.

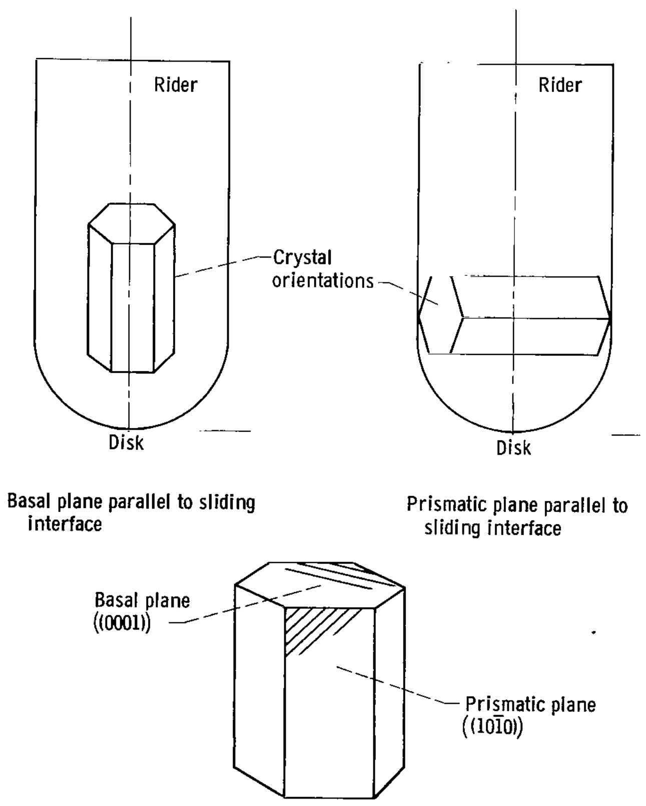


Figure 2. - Orientation of titanium single crystals (99.99 percent pure) with respect to rider and disk specimens.

Crystal Preparation and Orientation

Single crystals of high-purity titanium (99.99 percent) were obtained from a commercial source and oriented at this center. These crystals were grown from zone-refined titanium in the solid state by strain-annealing because of the crystal transformation associated with titanium. The crystals were rounded as shown in figure 2 by using a spark discharge. The crystal orientations were then determined by X-ray diffraction. Of the five single crystals with the prismatic plane nominally parallel to the sliding interface, three crystals were within 1° of the desired orientation, the fourth was within 7° to 10°, and the fifth was within 11°. The sixth crystal had the basal plane 7° from a parallel position to the sliding interface (fig. 2).

RESULTS AND DISCUSSION

Hexagonal metals exhibit basal slip when the critical resolved shear stress for the initiation of basal slip is less than that for prismatic slip. An example of this behavior is demonstrated for magnesium in figure 3 (ref. 5). With lower shear stresses a lower coefficient of friction should be expected. Those metals exhibiting basal slip would be expected to have lower coefficients of friction when the basal plane is oriented parallel to the plane of sliding than when the prismatic plane is parallel to the direction of sliding. Reference 3 supports this conclusion, in that, for cobalt, which slips on basal planes, a lower coefficient of friction was observed for sliding on a basal plane than for sliding on a prismatic plane.

The hexagonal metals, such as cobalt, zinc, magnesium, and cadmium, which exhibit basal slip do so because of lattice parameter and atomic bonding considerations. In these metals bonding is such that it facilitates shear between basal planes. For titanium, hafnium, and zirconium, the distance between basal planes is reduced and stronger bonding forces result. These bonds are stronger than the bonds between prismatic planes, and consequently the prismatic planes are the planes which slip initially. This is demonstrated by the data of figure 3 (refs. 6 and 7) for titanium single crystals. The shear stress for prismatic slip $((10\bar{1}0))$ is less than half of that for basal slip $((0001))$.

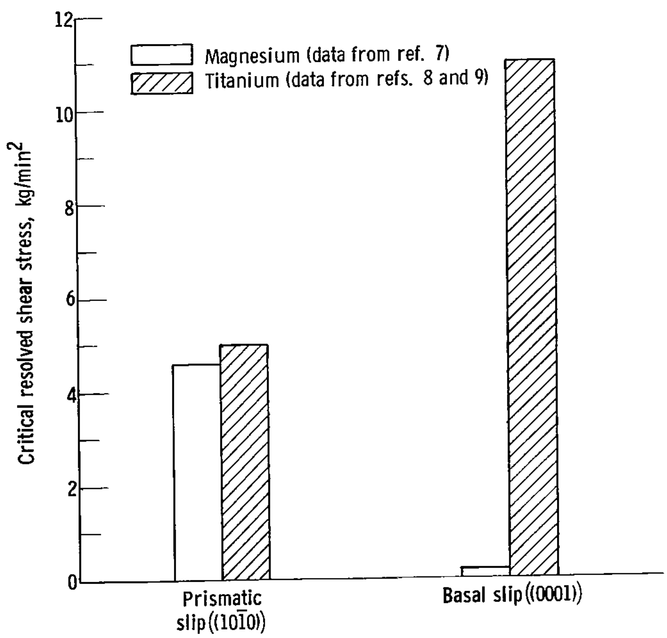


Figure 3. - Critical resolved shear stress associated with basal and prismatic slip for magnesium and titanium.

Since a dependence of friction coefficient on slip behavior was noted for cobalt in reference 3, experiments were conducted in vacuum with titanium single crystals to determine if such a relation exists for titanium. Friction experiments were conducted with two titanium single-crystal orientations. With one crystal orientation the prismatic plane

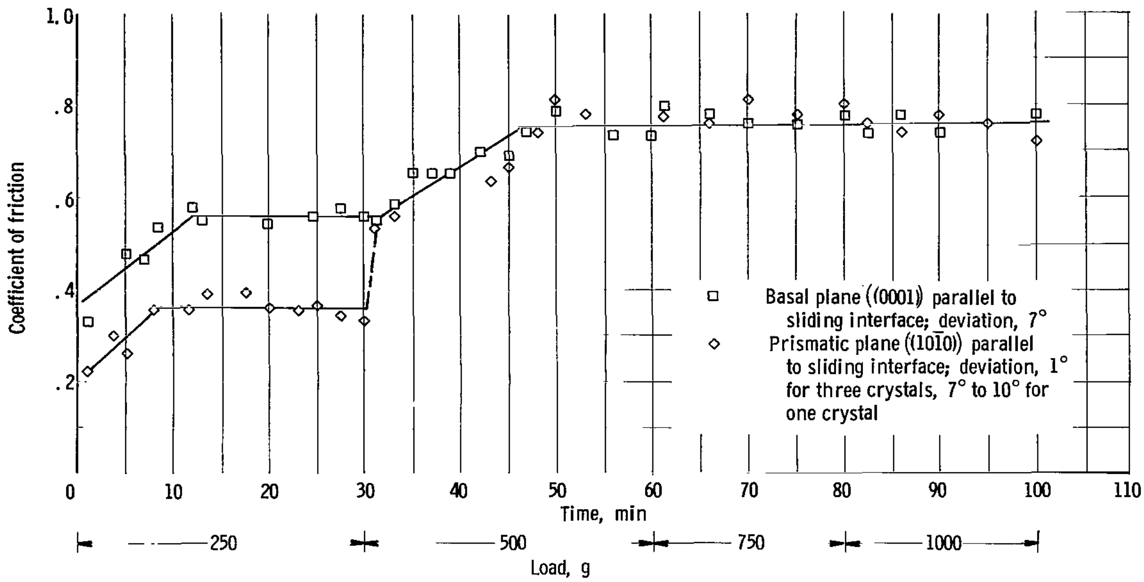


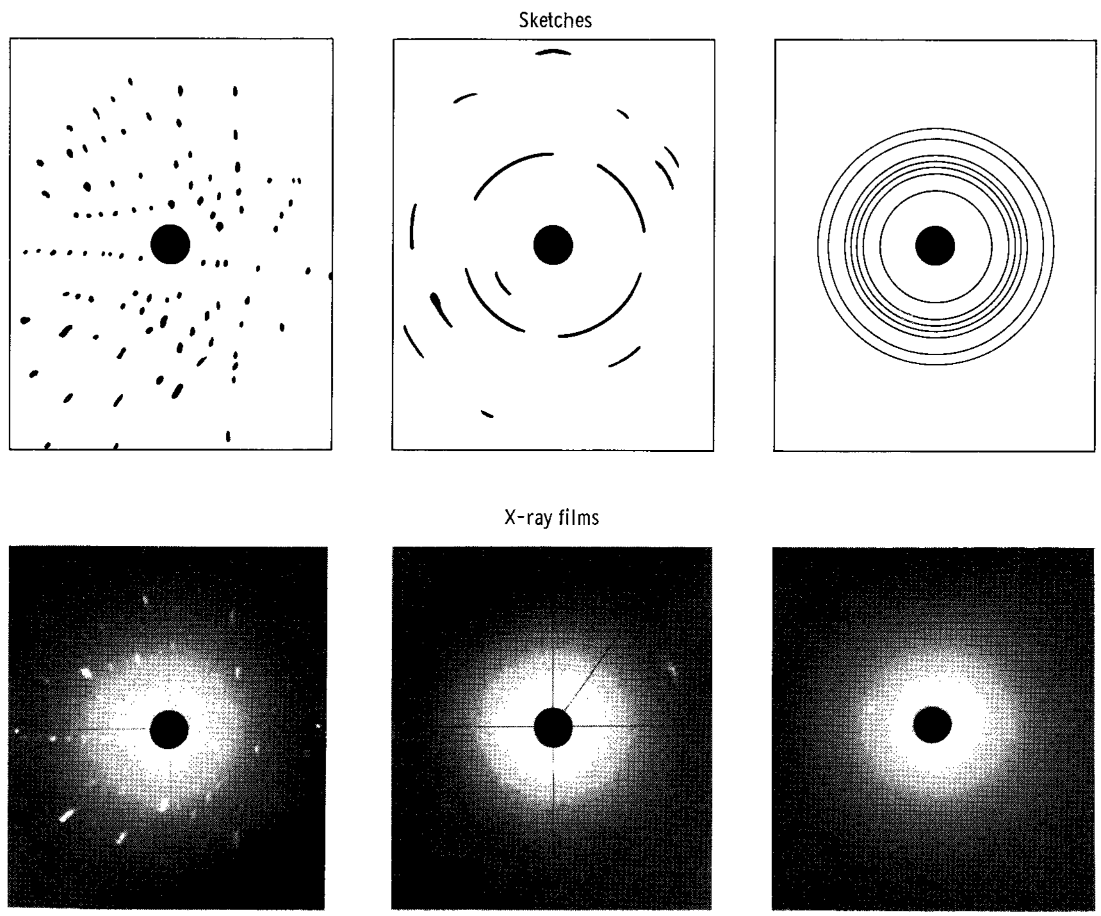
Figure 4. - Coefficient of friction for titanium single crystals (99.99 percent pure) sliding on polycrystalline titanium. Sliding velocity, 2.28 centimeters per second; ambient pressure, 10^{-9} millimeter of mercury, no external heating of specimens.

was nearly parallel to the sliding interface (fig. 2). The deviation from a parallel orientation was from 1° to 10°. With the second orientation the basal plane was nearly parallel to the sliding interface with a deviation of 7° (fig. 2). The results obtained in friction experiments with these crystals are presented in figure 4. The friction results obtained with a 250-gram load indicate that the prismatic plane $\left((10\bar{1}0)\right)$ does exhibit lower friction than the basal plane $\left((0001)\right)$. These results are in agreement with the shear-stress data of figure 3 for titanium. With different crystals various degrees of deviation for the prismatic plane parallel to the plane of sliding were measured. Friction results, however, did not indicate any significant difference between 1° and 10° deviations from a parallel orientation. When the load on the single crystals was increased from 250 to 500 grams, the friction coefficient increased as shown in figure 4. At this higher load (500 g) both crystal orientations exhibited very nearly the same friction values. With a further increase in load, first to 750 and then to 1000 grams, no further increase in friction was observed over the results obtained at a load of 500 grams. These results indicate that the nature of the interfacial structure must be nearly the same at loads of 500, 750, and 1000 grams.

The increase in friction first noted with the two single crystals in figure 4 to a common value at a 500-gram load was believed to be due to recrystallization at the sliding interface with the formation of a textured surface. The evidence for this conclusion was obtained from (1) the friction data of figure 4, (2) X-ray diffraction patterns, (3) the recrystallization temperature for titanium, (4) the thermal conductivity of titanium, (5) achievable interface temperatures, and (6) friction data for single-crystal and polycrystalline titanium. These points will be discussed in order.

The friction data of figure 4 for the 500-gram load indicate no difference in the coefficient of friction for two single crystals of different orientations with correspondingly different shear properties and friction coefficients at a lighter load. It might be conjectured that such an effect is due to the initiation of duplex slip (prismatic and basal). If duplex slip were to occur, a difference in friction coefficient would still be expected. At 250 grams, however, the friction values for the individual planes are observed, while at 500, 750, and 1000 grams the same friction coefficients are obtained for both crystals.

Upon completion of friction experiments X-ray diffraction patterns were obtained on the wear scar present on the titanium single-crystal surface. The X-ray patterns for the wear scar, the pattern behavior before the experiment, and a pattern for randomly oriented polycrystalline titanium are presented in figure 5. Above each print from the film is a sketch of what is present on the film. For the oriented single crystal, single spots are observed (fig. 5(a)); for the randomly oriented polycrystalline aggregate, complete Debye rings are observed (fig. 5(c)). The partial arcs of figure 5(b), however, repre-



(a) Single crystal. (b) Single crystal after experiment. (c) Deformation-free polycrystal.

Figure 5. - X-ray back-reflection patterns of single and polycrystalline titanium.

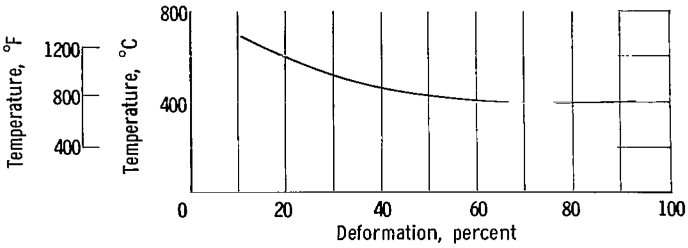


Figure 6. - Recrystallization temperature of titanium at various deformations. (Data from refs. 11 and 12.)

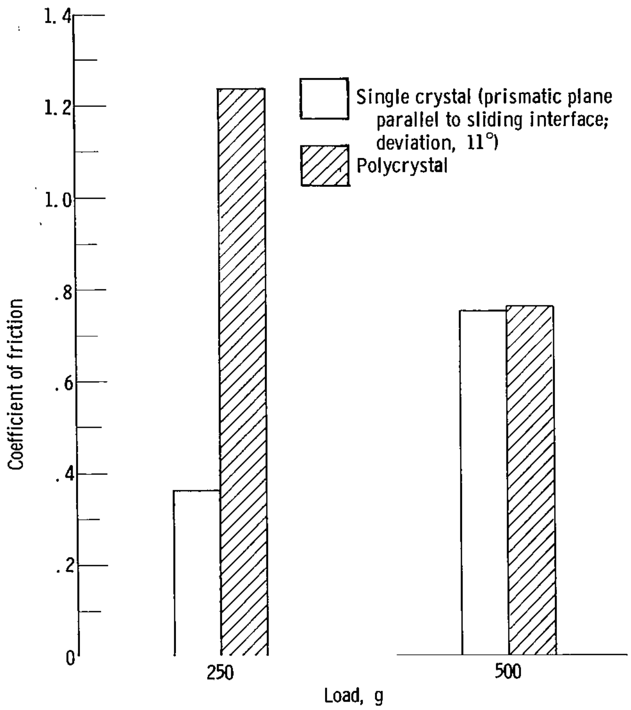


Figure 7. - Coefficient of friction for single and polycrystalline titanium sliding on polycrystalline titanium in vacuum (10^{-9} mm Hg). Sliding velocity, 2.28 centimeters per second; no external heating of specimens.

sent patterns for highly oriented polycrystalline material (refs. 8 and 9). It would therefore appear that a thin film of a polycrystalline material is present on the single-crystal wear scar.

Additional evidence for recrystallization of titanium at the sliding interface may be obtained from an examination of figure 6. The curve of figure 6 represents the recrystallization temperature for titanium as a function of plastic deformation. This curve represents a summary of data taken from references 10 and 11. Examination of figure 6 would indicate that, with 60 percent plastic deformation, recrystallization of titanium will occur at 400° C. The plastic deformation at a sliding interface can easily achieve such percentages.

Temperatures of 400° C at a sliding interface in vacuum are not difficult to achieve. References 12 and 13 discuss in detail interface temperatures during sliding. These references coupled with the vacuum environment of this investigation, where heat dissipation is very difficult, lend further evidence to the achievement of the recrystallization of titanium at the sliding interface.

Some additional evidence for titanium recrystallization at the sliding interface is gained from data obtained in this investigation for single-crystal and polycrystalline titanium which are presented in figure 7. At a load of 250 grams with a single crystal oriented with the prismatic plane parallel to the sliding interface, a friction coefficient of 0.36 was obtained. With a polycrystalline titanium specimen, a friction coefficient of 1.23 was obtained. The polycrystalline specimen had been heated in vacuum to 1000° F for 24 hours prior to friction studies to remove residual stresses. X-ray diffraction showed a random distribution of crystallite orientations. These results are in agreement with shear-stress data obtained with metals in references 14 and 15 which show that with polycrystalline material much higher shear stresses are observed than with single crystals having single or multiple slip. When the load was increased from 250 to 500 grams (fig. 7) for both single-crystal and polycrystalline titanium, essentially the same friction values were obtained (about 0.75). The possible effect of work-hardening for the materials must be discounted because both single crystal and polycrystal forms exhibit the same friction coefficient yet possess different hardening mechanisms. If both materials have the same friction coefficients, they can be assumed to have the same shear strength at the sliding interface and, therefore, nearly the same physical makeup. The mechanism which is felt to explain this behavior is recrystallization with texturing (preferred orientation) of the interface surface. For the single crystal recrystallization introduces grain boundaries which are shown in reference 14 to introduce barriers to dislocation motion. This action results in an increase in shear stress, and hence friction coefficient, for the single crystal with the recrystallized and textured surface film. Recrystallization followed by preferred orientation of crystallites for the polycrystalline material can be expected to result in a decrease in shear stress of a randomly oriented material in a polycrystalline matrix. This can be expected to occur as a result of the decreasing tendency for slip plane interaction (ref. 5). Consequently, the friction for the oriented polycrystal can be expected to decrease. At the higher loads both the single-crystal specimens and the randomly oriented polycrystalline specimens have the same interface surface, namely, a highly textured or oriented polycrystalline material which has resulted from recrystallization at the interface followed by texturing.

SUMMARY OF RESULTS

The following results were obtained from an investigation of the friction characteristics of titanium single crystals in a vacuum:

1. With oriented titanium single crystals sliding on polycrystalline titanium a lower friction coefficient was obtained when the single crystals were oriented with the prismatic plane $\left((10\bar{1}0)\right)$ parallel to the direction of sliding than when the crystals were oriented with the basal plane $\left((0001)\right)$ in the same direction. These results correlate with critically resolved shear-stress data which show that the stress for shear is lower on the prismatic than on the basal plane.

2. At high load conditions (1000 g) recrystallization of titanium occurred at the sliding interface of single crystals with the formation of recrystallization texturing.

3. The friction data for the single crystal which recrystallizes very closely approximated those for polycrystalline titanium sliding on polycrystalline titanium. These results would seem to indicate that at high loads or speeds (where interface deformation is

severe) a highly oriented recrystallized polycrystalline material is obtained whether the bulk material is single crystal or polycrystalline.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 7, 1965.

REFERENCES

1. Buckley, Donald H.; Kuczkowski, Thomas J.; and Johnson, Robert L.: Influence of Crystal Structure on the Friction and Wear of Titanium and Titanium Alloys in Vacuum. NASA TN D-2671, 1965.
2. Buckley, Donald H.; and Johnson, Robert L.: Relation of Lattice Parameters to Friction Characteristics of Beryllium, Hafnium, Zirconium and Other Hexagonal Metals in Vacuum. NASA TN D-2670, 1965.
3. Buckley, Donald H.; and Johnson, Robert L.: Marked Influence of Crystal Structure on the Friction and Wear Characteristics of Cobalt and Cobalt-Base Alloys in Vacuum to 10^{-9} Millimeter of Mercury. I - Polycrystalline and Single Crystal Cobalt. NASA TN D-2523, 1964.
4. Buckley, Donald H.; and Johnson, Robert L.: Influence of Crystal Structure on Friction Characteristics of Rare-Earth and Related Metals in Vacuum to 10^{-10} Millimeter of Mercury. NASA TN D-2513, 1964.
5. McLean, Donald: Mechanical Properties of Metals. John Wiley & Sons, Inc., 1962.
6. Rosi, F. D.; Dube, C. A.; and Alexander, B. H.: Mechanism of Plastic Flow in Titanium. J. Metals, vol. 4, Feb. 1952, pp. 145-146.
7. Anderson, E. A.; Jillison, D. C.; and Dunbar, S. R.: Deformation Mechanisms in Alpha Titanium. J. Metals, sec. 2, vol. 5, no. 9, Sept. 1953, pp. 1191-1197.
8. Barrett, C. S.: Structure of Metals. McGraw-Hill Book Co., Inc., 1943.
9. Cullity, B. D.: Elements of X-Ray Diffraction. Addison-Wesley Pub. Co., 1956.
10. Bartholomew, Edward L., Jr.: Grain Growth and Recrystallization in Titanium and Its Alloys, Pts. I-II. Rept. No. 401/131-13, Watertown Arsenal Lab., June 10, 1954.
11. Castleman, L. S.; Rossi, F. D.; and Seigle, L. L.: Recrystallization of Titanium. Rept. No. TR 55-321, WADC, Sept. 1955.

12. Bowden, F. P.; and Tabor D.: The Friction and Lubrication of Solids. Second ed., Oxford Univ. Press, Inc., 1958.

13. Blok, H. Theoretical Study of Temperature Rise at Surfaces of Actual Contact Under Oiliness Lubricating Conditions. Proc. Inst. Mech. Eng., vol. 2, 1937, pp. 222-235.

14. Jaswon, M. A.; and Richman, M. H.: Some Mechanical Effects of Grain Boundaries. Rept. No. TR-6, Brown Univ., June 1964.

15. McLean, Donald: Grain Boundaries in Metals. Clarendon Press (Oxford), 1957.

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